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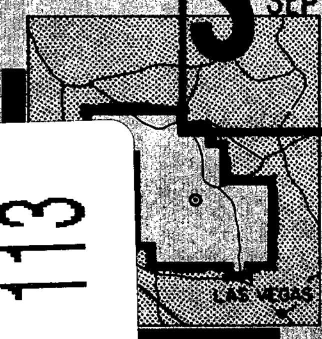
Operation UPSHOT-KNOTHOLE

NEVADA PROVING GROUNDS

March - June 1953

Program 3.28.2

PRESSURE MEASUREMENTS FOR VARIOUS PROJECTS OF PROGRAM 3



HEADQUARTERS FIELD COMMAND, ARMED FORCES SPECIAL WEAPONS PROJECT
SANDIA BASE, ALBUQUERQUE, NEW MEXICO

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OPERATION UPSHOT-KNOTHOLE

Project 3.28.2

PRESSURE MEASUREMENTS FOR VARIOUS PROJECTS OF PROGRAM 3

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REPORT TO THE TEST DIRECTOR

REGRADED ____________________

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by

W. E. Morris

J. Petes

B. Wode, 23 Sep 64

December 1953

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ABSTRACT

The Naval Ordnance Laboratory instrumented various Program 3 projects for pressure-time histories. The instrumentation system consisted of Wiancko inductance gages, FM intelligence generation, and magnetic tape data storage. Pressure measurements were made on three aboveground structures, one underground structure, five foxholes, a diffraction study layout around one of the aboveground structures, and a tree stand. The results of Shot 9 were excellent; 127 complete pressure-time records were obtained from the total of 128 stations instrumented. On Shot 10, 48 complete records and 48 partial records were obtained from the 105 stations instrumented. Broken cables caused by displacement of the structures accounted for most of the partial and total loss of records on this shot. The records were reproduced as pressure-time curves with pressure scales added and, along with instructions for record analysis and interpretation, were presented to the cognizant agencies for their analysis.

[redacted]

FOREWORD

This report is one of the reports presenting the results of the 78 projects participating in the Military Effects Tests Program of Operation UPSHOT-KNOTHOLE, which included 11 test detonations. For readers interested in other pertinent test information, reference is made to WT-782, Summary Report of the Technical Director, Military Effects Program. This summary report includes the following information of possible general interest:

a. An over-all description of each detonation, including yield, height of burst, ground zero location, time of detonation, ambient atmospheric conditions at detonation, etc., for the 11 shots.

b. Compilation and correlation of all project results on the basic measurements of blast and shock, thermal radiation, and nuclear radiation.

c. Compilation and correlation of the various project results on weapons effects.

d. A summary of each project, including objectives and results.

e. A complete listing of all reports covering the Military Effects Tests Program.

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PREFACE

This is the final report of Project 3.28.2, and it supersedes the preliminary report, UKP-30.

In addition to outlining the scope of the project, describing the instrumentation, and reporting results obtained, this report outlines in detail the mechanics of reading the records and points out in what way the instrumentation affects the accuracy and interpretation of the records. The reporting of the data is the responsibility of the agencies which sponsored the various projects and is not reported here.

The measurements for Projects 1.1a and 3.28.2 were combined and instrumented as a unit by the same personnel and instrumentation system.

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ACKNOWLEDGMENTS

This project was coordinated with the over-all structures program through the efforts of the Ballistic Research Laboratories.

Initial planning at the Naval Ordnance Laboratory was carried out with the assistance of Dr. G. K. Hartmann, Dr. P. M. Fye, Dr. J. E. Ablard, Dr. W. E. Morris, Mr. C. J. Aronson, and Mr. J. Petes.

The Naval Ordnance Laboratory is indebted to the Armed Forces Special Weapons Project for providing five military officers and six enlisted men to assist with the project. Appreciation is expressed for the administrative and logistic support provided by the Field Command, AFSWP, and CDR C. E. Langlois, Director Program 3.

Sincere appreciation is expressed to the project personnel who, working under a stringent time schedule and disagreeable field conditions, carried the project through to a successful completion. Personnel participating in this project were:

W. E. Morris	Project Officer
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F. J. Oliver	Group Leader
R. R. Boyd, Capt., USA	Associate Group Leader
E. J. Culling	Associate Group Leader
C. C. Little	Associate Group Leader
D. Overton, Capt., USA	Associate Group Leader
H. C. Davies, Capt., USAF	Administration
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The project is indebted to E. Zdanis for preparation of the report for publication.

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CHAPTER 1

INTRODUCTION

1.1 SCOPE OF THE PROJECT

The Naval Ordnance Laboratory (NOL), in conjunction with the Ballistic Research Laboratories and the Stanford Research Institute, assumed the responsibility for the instrumentation of the structures of Program 3. As its part of the instrumentation program the NOL made pressure measurements for Projects 3.1, 3.1u, 3.7, 3.9, 3.13, and 3.19.

1.1.1 Pressure-Time Measurements

For Program 3 a total of 128 pressure-time gages were installed for Shot 9 (8 May) and 105 pressure-time gages for Shot 10 (25 May). An outline of the pressure-time measurements follows:

(1) PROJECT NUMBER:	3.1
Sponsor:	U. S. Air Force
Performing Agency:	Wright Air Development Center
Title of Project:	Tests on the Loading of Building and Equipment Shapes
Structures:	3.1s and 3.1t, 6'x6'x12' non-deformable cubicles
Description of Measurements:	Pressure-time curves on the front, top, side, and rear of the structures
Number of Gages:	3.1s structure: 24 gages, Shot 9 24 gages, Shot 10 3.1t structure: 24 gages, Shot 9 24 gages, Shot 10

(2) PROJECT NUMBER:	3.1u
Sponsor:	U. S. Navy
Performing Agency:	Naval Ordnance Laboratory
Title of Project:	Shock Diffraction Studies in the Vicinity of a Structure

[redacted]

Structure:	Area in the vicinity of 3.1t structure
Description of Measurements:	Pressure-time measurements in the vicinity of the 3.1t structure
Number of Gages:	14 gages, Shot 9 14 gages, Shot 10
(3) PROJECT NUMBER:	3.7
Sponsor:	U. S. Army
Performing Agency:	Office, Chief of Engineers
Title of Project:	Air Blast Effects on Entrances and Air Intakes of Underground Installations
Structure:	3.7 Underground structure
Description of Measurements:	Pressure-time measurements in the walls of shelter entrances, air intake and outlet pipes and plenum chambers
Number of Gages:	34 gages, Shot 9 34 gages, Shot 10
(4) PROJECT NUMBER:	3.9
Sponsor:	U. S. Army
Performing Agency:	Engineering Research and Development Laboratory
Title of Project:	Field Fortifications
Structure:	Five foxholes
Description of Measurements:	Pressure-time measurements in the bottom of foxholes
Number of Gages:	5 gages, Shot 9 5 gages, Shot 10
(5) PROJECT NUMBER:	3.13
Sponsor:	U. S. Navy
Performing Agency:	Bureau of Yards and Docks
Title of Project:	Precast Gable Structure, Without Earth Cover
Structure:	3.13b precast gable structure
Description of Measurements:	Pressure-time measurements on the side, end, and top walls of the structure
Number of Gages:	12 gages, Shot 9
(6) PROJECT NUMBER:	3.19
Sponsor:	U. S. Army
Performing Agency:	U. S. Department of Agriculture
Title of Project:	Blast Damage to Coniferous Tree Stands by Atomic Explosions

[redacted]

Structure:	Array of trees
Description of Measurements:	Pressure-time measurements on the ground and at several heights within the tree stand
Number of Gages:	15 gages, Shot 9 4 gages, Shot 10

1.1.2 Peak Pressure Measurements

In addition to the pressure-time gages, a few NOL indenter gages, which measure peak pressure, were installed on the 3.1s and 3.1t structures and in two of the Project 3.9 foxholes. These gages were installed on an experimental basis primarily for gage evaluation purposes and this instrumentation, therefore, is not considered germane to this report. A brief description of the indenter gage installation appears in Appendix A and the results are summarized in reference (1).

In regard to peak pressure measurements with indenter gages, mention is made of the fact that the NOL made available 100 indenter gages to Project 3.9 and provided instruction in their use.

1.2 OBJECTIVE

The objective of this project was to make pressure-time measurements on and about various structures and installations of Projects 3.1, 3.1u, 3.7, 3.9, 3.13, and 3.19 and to present the resulting data in the form of pressure-time curves to the cognizant agencies for their analysis.

[redacted]

CHAPTER 2

PROCEDURE, INSTRUMENTATION, AND LAYOUT

2.1 PRESSURE-TIME INSTRUMENTATION

2.1.1 General

The instrumentation used for pressure-time measurements on Projects 1.1a and 3.28.2, Operation UPSHOT-KNOTHOLE, was a frequency modulation system using inductance gages, unshielded transmission wire, and magnetic tape data storage. Two gage signal frequencies, one centered at 15.4 kc, and the other at 10.7 kc, were diplexed on one transmission and recording channel in order to accommodate the required large number of gages with economy of time, effort and equipment. The recording instrumentation was housed in two van type trailers located in underground revetments at 7000 ft and 11,500 ft from ground zero. Each recording trailer provided the power for and recorded the signals from approximately 85 gages per shot. The pressure gages and associated oscillators and amplifiers were located in the field at the various stations in appropriate mounts. All recording instrumentation controls were unmanned at shot time and remotely operated.

After each shot, the eight magnetic tapes from each recording trailer were recovered and played back at a trailer facility. Here the magnetic signal variations on the tape were converted into records graphically depicting pressure versus time at the various gage positions, and these records were then analyzed and interpreted.

The over-all maximum response of the system was such as to respond to a step-wise positive pressure pulse in 0.2 to 0.3 milliseconds (ms), the gage response being the limiting factor.

2.1.2 Gages

The P-1407 type of Wiancko twisted tube inductance gage was used on this operation (2). This gage contained only one coil of approximately 110 millihenries inductance with a tap at about 40 millihenries. The coil comprised the inductance of the tank circuit

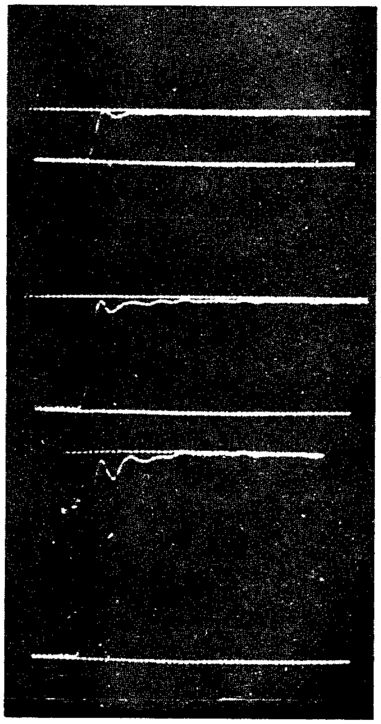
[redacted]

of the Hartley oscillator used for signal generation. The twisted tube sensing element with its attached armature changed the inductance of the coil, and thus the frequency of the oscillator, in step with the forcing pressure signal. This provided the means of intelligence generation.

Fluid damping was used in the gages to obtain optimum dynamic and transient response. Some difficulty was experienced with the damping in that for 0.6 to 0.7 critical damping at 70° F many gages exhibited a "creep" when a step-wise pressure function was applied. Initially, the rise time of the record, 0.3 to 0.8 ms, would be compatible with the manufacturer's stated response of the gage, but at about 90 per cent of the applied pressure signal the gage would respond more slowly, "creeping" up to the applied pressure value in 5 to 25 ms (Fig. 2.1). With the limited time available both to NOL and Wiancko for further gage design research, a working compromise had to be reached between damping and "creep"; therefore, the damping coefficient was lowered to the point where "creep" was eliminated even though the damping coefficient went down to 0.2 to 0.4 critical. This, of course, adversely affected the overshoot and ringing characteristics of the gage when the forcing function had a rise time equal to or less than the response time of the gage (Fig. 2.2). However, even with the decreased damping, most gages stopped ringing in less than 3 ms; a few extended out to 5 ms. (This degree of ringing is a considerable improvement over the Bendix inductance gage used by NOL in previous operations, where the true pressure signal had to be extrapolated through 30-40 ms of ringing.)

Another adverse characteristic was noted in the Wiancko gage; namely, hysteresis. A gage which was cycled in a positive pressure direction would not return to the original rest position when the pressure was brought back down to ambient atmospheric pressure. Further, a recalibration run of the gage would result in a slightly but significantly different pressure-frequency curve. For most gages the hysteresis error at ambient pressure was no more than 0.75 per cent of the maximum pressure range and could be corrected only in data analysis. To insure repeatability of gage performance and calibration and to partially eliminate the effects of hysteresis, all gages were cycled in both a positive and negative pressure direction in the field. Field calibrations were then compared with laboratory calibration and only those gages which showed good calibration agreement were used.

The Wiancko gage used by the NOL was acceleration sensitive. Various electromechanical and electrical testing procedures (2) showed that the electrical sensing element of the gage (mu metal armature) could be displaced from its equilibrium position in three distinct paths - rotationally in torsion (the gages being designed to respond to this type of motion), and translationally in two cantilever modes mutually perpendicular one to the other (extraneous motions). With each of these motions was associated a partic-

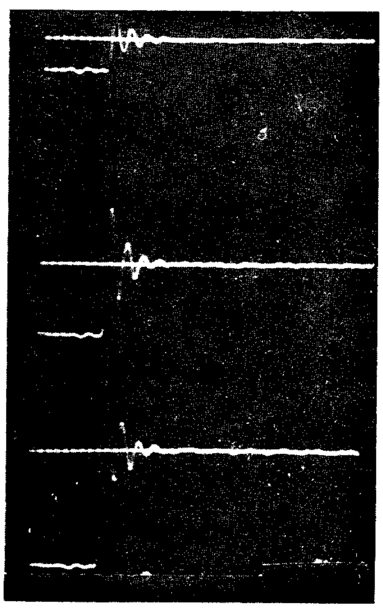


5 PSI STEP PRESSURE

10 PSI STEP PRESSURE

14 PSI STEP PRESSURE
(2 kc TIMING FREQUENCY)

Fig. 2.1 Creep Characteristic of a Wiancko Gage



5 PSI STEP PRESSURE

10 PSI STEP PRESSURE

14 PSI STEP PRESSURE
(2 kc TIMING FREQUENCY)

Fig. 2.2 Dynamic Characteristics of a Wiancko Gage

[redacted]

ular resonant frequency. These modes of motion could be excited by either the sinusoidal application of acceleration as with a shake table, or by shock excitation. Striking the gage mounting plate with a hammer blow or a shock wave produced in a shock tube gave rise to signal outputs from the gage. The magnitude of this acceleration response was, for example, equivalent to a 1 psi signal on a 20 psi nominal rated gage for a 10 g drop. These acceleration effects made difficult the interpretation of the pressure records, particularly on Shot 10.

How the various gage characteristics such as acceleration effects, hysteresis, and underdamping affected the pressure records, and the method of interpreting the records in view of these characteristics is discussed in Appendix B.

2.1.3 Oscillator-Amplifier

A one tube oscillator-amplifier circuit was used for each gage position with filament and plate power being provided remotely from the recording trailers. One section of the dual triode 12AU7 tube was used in a shunt-fed Hartley oscillator, the other half in a buffer amplifier between the oscillator and line. At most stations two oscillator-amplifier signals were mixed, the 15.4 kc and the 10.7 kc signals being diplexed across a linear bridge network to minimize distortion and intermodulation. The composite signal of the two oscillators or the single signal of a single station was then coupled to the transmission line with an appropriate impedance matching network.

2.1.4 Transmission Line

The signal and power transmission line to each single and/or double channel consisted of two pairs of twisted, unshielded field telephone wire of the type Signal Corps WD-1/TT. One pair of the wires was used for carrying AC filament power to the field oscillator-amplifiers; the other pair served the dual purpose of carrying DC plate voltage to the field units and transmitting the signal frequencies back to the recording instrumentation. The signal transmission pair was terminated with the proper impedance at both sending and receiving ends. The power and signal levels were of such amplitude as to override line losses and enable cable lengths of as long as 3 miles to be used without intermediary amplification between the field units and the recording trailers. For thermal and blast protection, the field wires were buried under 2 ft of earth.

Limited field tests on Operation TUMBLER and extensive tests in the laboratory indicated that it was entirely feasible to use unshielded wire in the NOL FM system without adverse cross-talk, intermodulation, or distortion of signals produced by NOL or other operating activities. The low initial cost, great strength, and ease

in handling dictated the use of the WD-1/TT wire instead of the shielded MCOS-6 cable used on previous operations.

2.1.5 Recording Trailer

Each recording trailer contained eight, seven-channel Ampex magnetic tape recorders (Model 304-1s), associated electronic equipment, relay control circuits, and four primary power sources as used on JANGLE (3) and TUMBLER (4) (Fig. 2.3). Each power source, consisting of a series-parallel arrangement of batteries driving a motor-generator set, provided AC and DC voltages to two recorders and the power supplies for gage-oscillator units connected to these recorders. Each of these four banks of power and instrumentation was operated by means of individual Edgerton, Germeshausen and Grier (EG&G) relay signals. Thus the four banks of equipment in each trailer were completely independent of each other, thereby providing a high degree of insurance against total loss of records in case of timing signal, power, or recorder failure.

Individual power supplies (dynamotors for plate voltage and auto-transformers for filament voltage) located in the trailers were used for each channel*. This design provided optimum operating conditions for each field unit and also guarded against mass loss of records. The signal of each channel was fed onto a single head of the recorders. Six heads of each recorder were used for gage signals and the seventh head recorded a common frequency calibration and time fiducial signal (Fig. 2.4), thus correlating all records in a trailer. In all, each trailer had 48 channels available for recording a maximum of 96 diplexed gage signals. The channels for any one program were distributed over at least eight recorders in a trailer, once again to minimize the possibility of major loss of records.

Prior to shot time, all switches and controls were left in a ready condition; at shot time backed-up sets of EG&G relay signals initiated the various recording functions.

2.1.6 Playback

After the shot, the magnetic tapes were recovered and played back. The magnetic variations on the tape were converted into electrical signals on the Ampex Reproducer track by track. These signals, in the form of frequency modulations, were converted into variations of amplitude with time in discriminator units and presented in graph-

* A "channel" as used in this report consists of the signal on one set of transmission wires and recorded by a single head. A channel in the majority of instances on this operation contained a composite signal consisting of a 15.4 kc signal from one gage position or station and a 10.7 kc signal from a nearby gage station; some channels, however, transmitted the signal from only one gage station.

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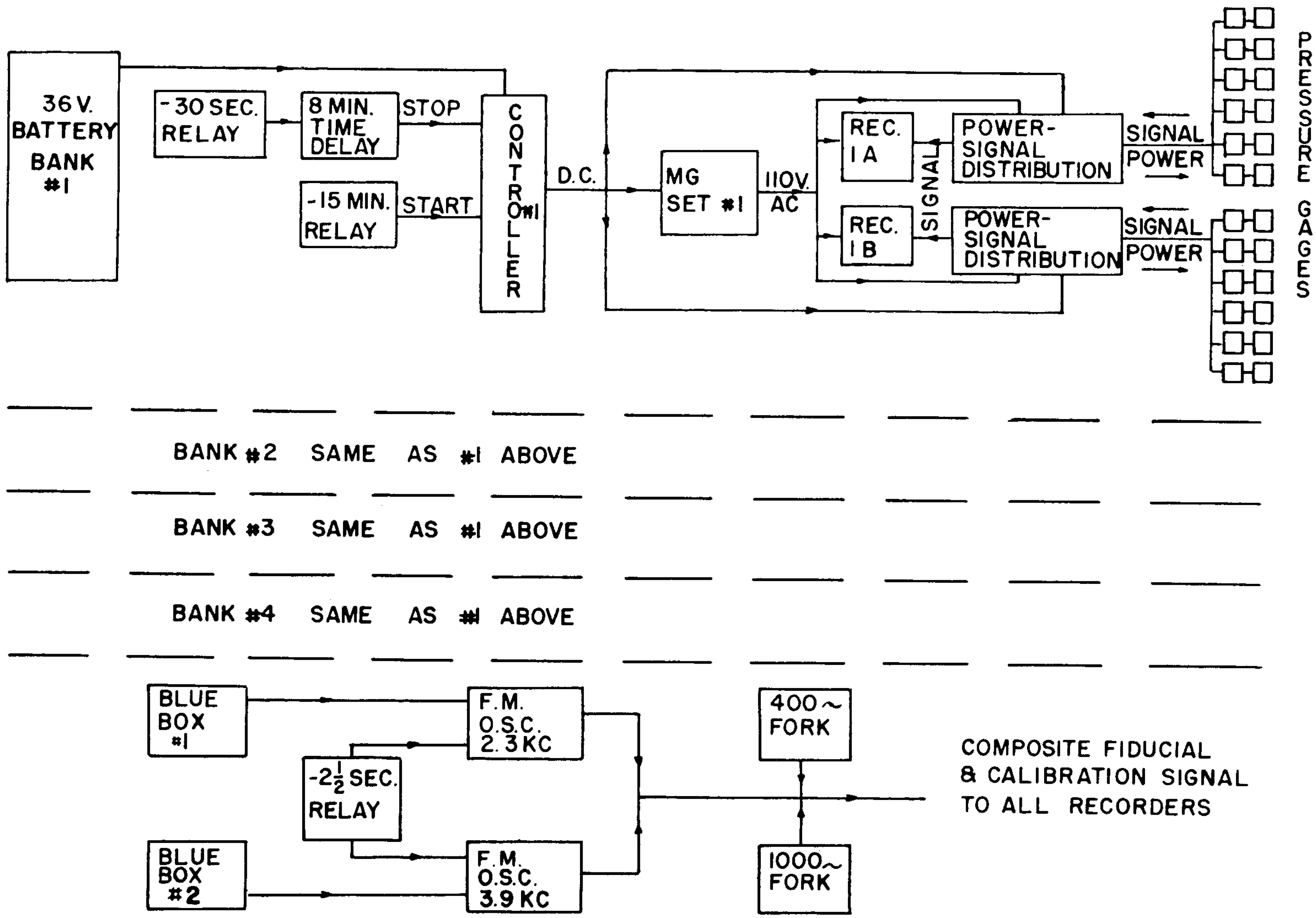

Fig. 2.3 Over-all Instrumentation System of Each Recording Trailer

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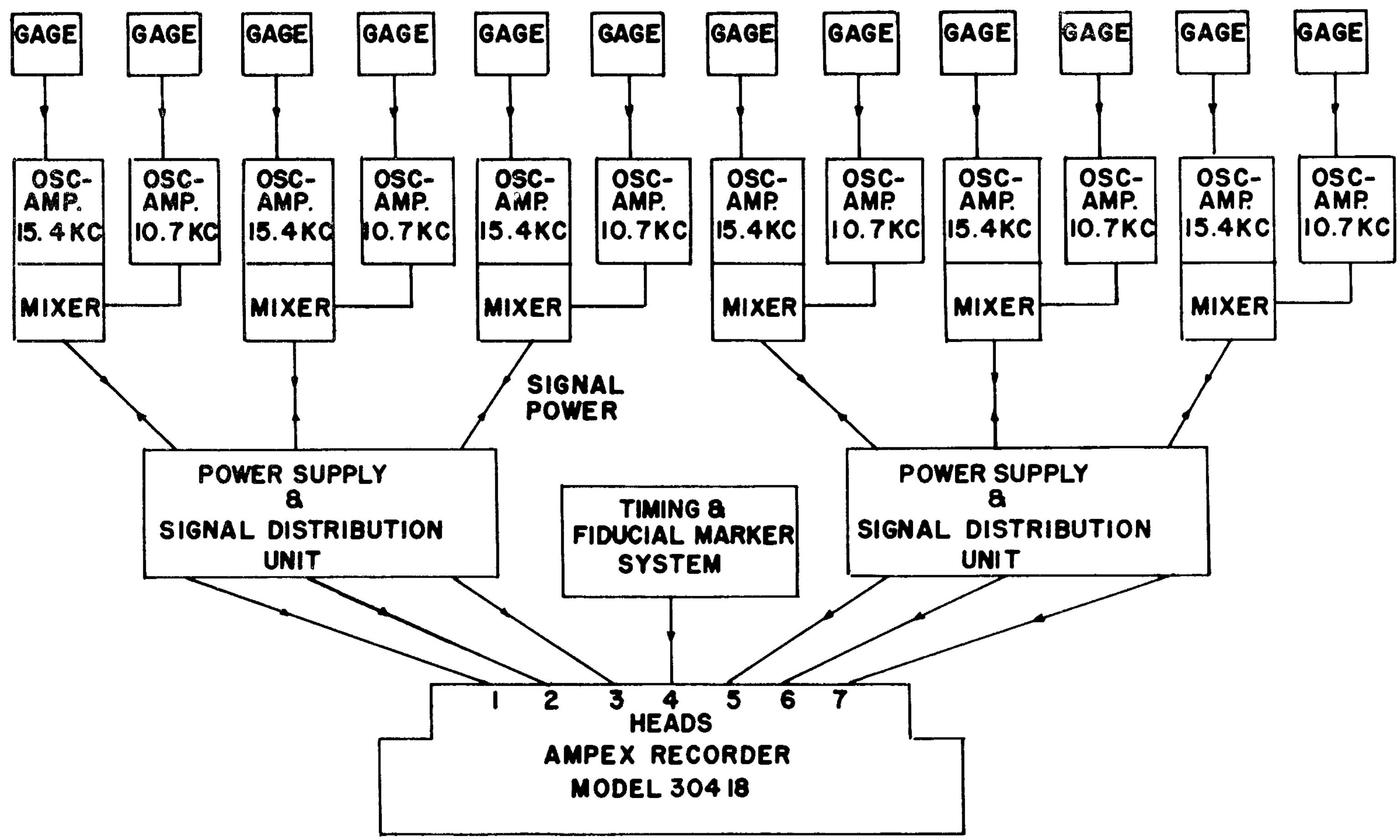

Fig. 2.4 Typical Field Recording System - Block Diagram

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ical form by a Century string oscillograph. The composite signal on the various tracks was divided into its two constituent signals by means of band pass filters in each discriminator unit so that the original gage induced center frequency variations were recovered as separate pressure signals (Fig. 2.5).

Simultaneously with the reproduction of each signal recording track, the frequency calibration and time fiducial head was played back. The frequency calibration was monitored and this made it possible to play back the signals at the proper tape speed for faithful frequency reproduction; it also permitted using post-recording amplitude calibrations for the pressure-time oscillogram. The fiducial timing signal also was recorded on the final pressure-time oscillogram, thus giving a common time reference for all records.

The String oscillograph was run at two speeds; at 6 in./sec to show gross qualities of the pressure-time history, and at 50 in./sec to obtain details of the points of interest in the shock wave record, particularly the initial rise to peak pressure.

2.1.7 System Errors

The response characteristics of the over-all instrumentation from gage to final record is that of an underdamped non-linear system. (The gage is the prime contributor to both the underdamped and non-linear characteristics.) This means, in a simple case, that if a known valued step function of pressure were applied to a gage, the final graphic record would show not a pure step function but rather a composite trace made up of the forcing step function and an exponentially decaying sinusoidal oscillation superimposed on the initial portion of the step. (The damping photographs of Fig. 2.2 are good examples of the type of final record obtained when a square step of pressure is applied to a gage.)

Quite obviously the record is not a faithful reproduction of the forcing function; it is in error at any point by the degree of departure from the known step value. For an underdamped system this error can be easily in excess of 50 per cent at the first overshoot. However, by proper and realistic interpretation of the record the error in the cited example can be reduced to approximately 2.5 per cent. This interpretation has to be based on a knowledge of the various response characteristics of the instrumentation used in obtaining the records and also on some prior knowledge of the characteristics of the forcing function. Thus, by fairing a line through the oscillations on the simple record under consideration, a compensation or correction for the known undamped characteristics of the system is obtained and the true form of the input pressure signal is reconstructed.

In this simple square step example, the loci of the faired line can be determined quite accurately and most of the error in arriving at a true numerical value for the recorded signal is due to

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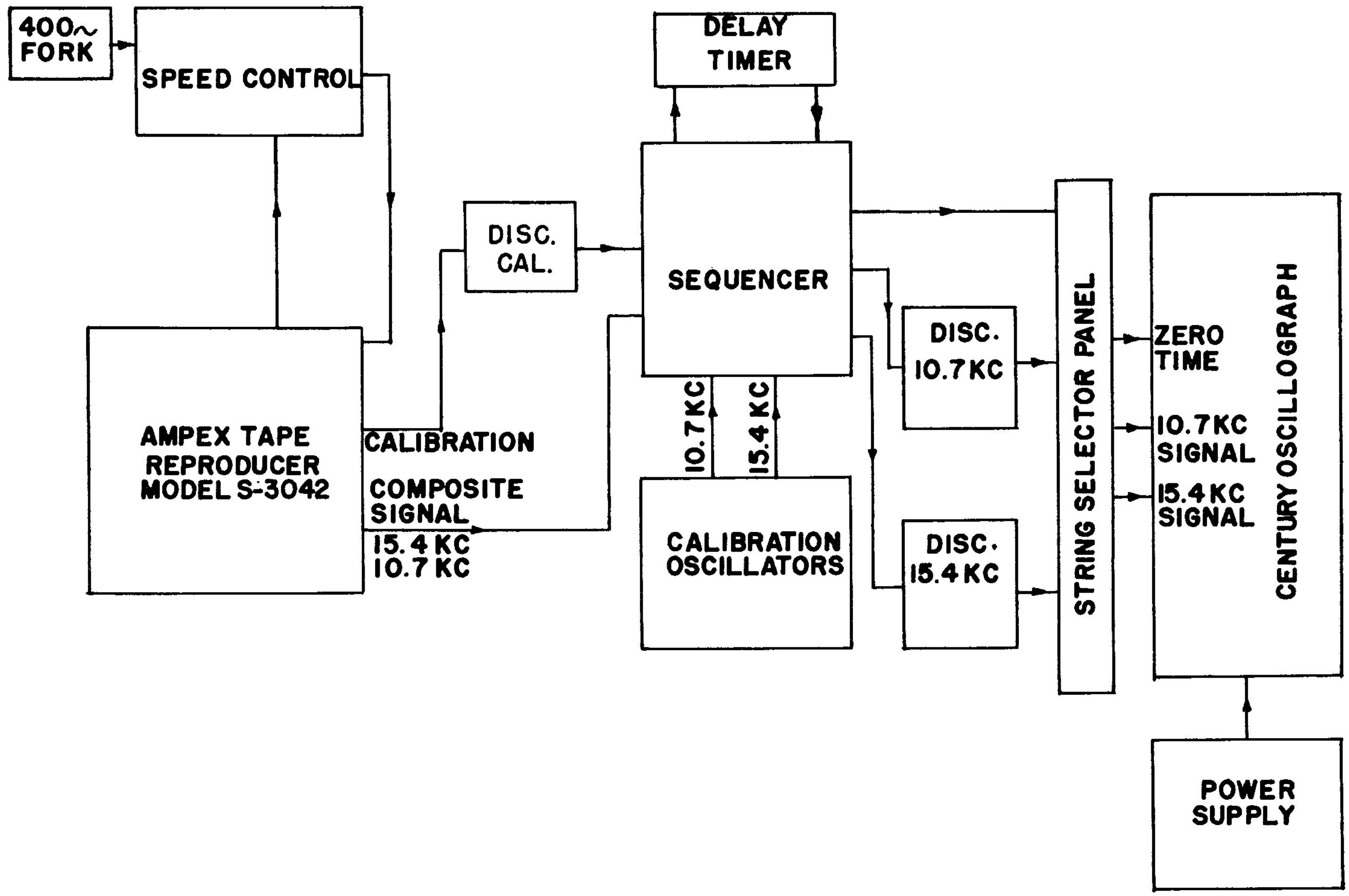

Fig. 2.5 Magnetic Tape Playback System - Block Diagram

[redacted]

inherent instrumentation and reading error. This error for the NOL FM system is approximately ± 2.5 per cent at maximum; i.e., the numerical value of any selected point on the record can be in error by a maximum of ± 2.5 per cent. These errors are made up primarily of calibration errors, recording and playback speed synchronization errors, and limitations of record reading resolution.

For an exponentially decaying forcing function such as the "text book" type of "clean" shock wave, it is only a little more difficult than for a square step function to fair a line through the extraneous oscillations and thus extract the true form of the excitation pulse. For an irregularly shaped forcing pressure, however, it is much more difficult to determine the true form of the input signal from the record and particularly so if the exact form of the input signal is not known - which is the case quite often. However, once again, by a judicious application of the known responses of the instrumentation with whatever information is available as to the nature of the pressure signal, a reasonable faired line can be determined for all records. It is believed that this fairing process produces errors of no more than ± 3 per cent for "clean" shock waves and ± 7 per cent for "hashed-up" records. As before, the accuracy of determining the numerical value of any point selected on the record is ± 2.5 per cent.

One other factor enters into a discussion of errors. The ratio of the measured signal amplitude to the nominal gage range amplitude influences the degree of accuracy obtained. For ratios > 0.5 the above stated figures are correct; for ratios < 0.5, the errors increase, becoming greater as the ratio decreases. Thus, negative pressure values may be in error by as much as ± 20 per cent.

Summarizing, the error in pressure determination is made up of two parts - an instrumentation error and a "selection" or "judgment" error. The numerical value associated with a selected point on the record can be established to within ± 2.5 per cent (provided the signal to gage range ratio is > 0.5); the selection of the point to be read can be in error by approximately ± 3 per cent, ± 7 per cent or greater, depending upon the assumed shape of the pressure signal and the relative magnitude of the signal. Thus, at a maximum, the errors in pressure determination can be ± 5 per cent, ± 10 per cent or greater. The average errors should be less than these figures.

When the hysteresis cycle of the gage calibration curve is used, decreasing pressures in the positive phase of the shock wave will have the same accuracy as the increasing pressures.

Time resolution of the system was approximately 0.2 ms, and timing errors approximately 0.05 per cent. However, due to the gradual approach of the pressure trace to the base line and the resulting difficulty of determining the crossover point, and also due to gage hysteresis, positive and negative phase durations are in error by approximately ± 8 per cent. Phase duration errors have only a second order effect on impulse measurements. Therefore, impulse measurements are in error by approximately the same degree as

[redacted]

pressure measurements.

Directions for reading NOL FM records are included in Appendix B.

2.2 PROCEDURE AND LAYOUT

2.2.1 General

All pressure gages were flush mounted in the structures, ground mounts, and vertical baffle plates. At those stations where the wall or mount thickness was at least 1 ft, both the gages and oscillator-amplifier units were housed in 6 in. or 9 in. diameter pipe-lined holes. At other stations the gages were mounted at the required locations and connected to the oscillator-amplifier by means of a low capacitance, shock insensitive cable (RG-22/U).

2.2.2 Project 3.1 Layout

The identical non-deformable structures, 3.1s and 3.1t, were each instrumented with 24 gages. The structures were 6 ft wide by 6 ft high by 12 ft long. Gage locations are shown in Fig. 2.6. The 12 channels (24 gages) for the 3.1s structure were distributed over the eight recorders of trailer 2. The 12 channels for the 3.1t structure were similarly distributed over the eight recorders of trailer 1. Identical instrumentation was employed on Shots 9 and 10.

2.2.3 Project 3.1u Layout

An array of pressure-time gages at ground level and at a height of 5 ft were located in the immediate vicinity of structure 3.1t. Fourteen gage stations were arranged in three lines, one directly behind the structure, one to the side of the structure, and the third at approximately a 45° angle (Fig. 2.7). The gage oscillator housings and baffles were identical to those used on the blast line measuring program and the signals were recorded by trailer 1. The vertical aboveground baffle plates were oriented 5° off intended ground zero in such a way as to provide pressure incidence on the front face (gage entry side) of the baffle plate rather than on the back face in case of moderate bombing error. Identical instrumentation was employed on Shots 9 and 10.

2.2.4 Project 3.7 Layout

The underground structure of Project 3.7, located at 900 ft from intended ground zero (Fig. 2.8) is comprised of entryway A (Fig. 2.9), entryway C (Fig. 2.10), and plenum chambers between the entryways (Fig. 2.11). This structure was instrumented with 34 gages, including a measurement at ground level between the two entry-

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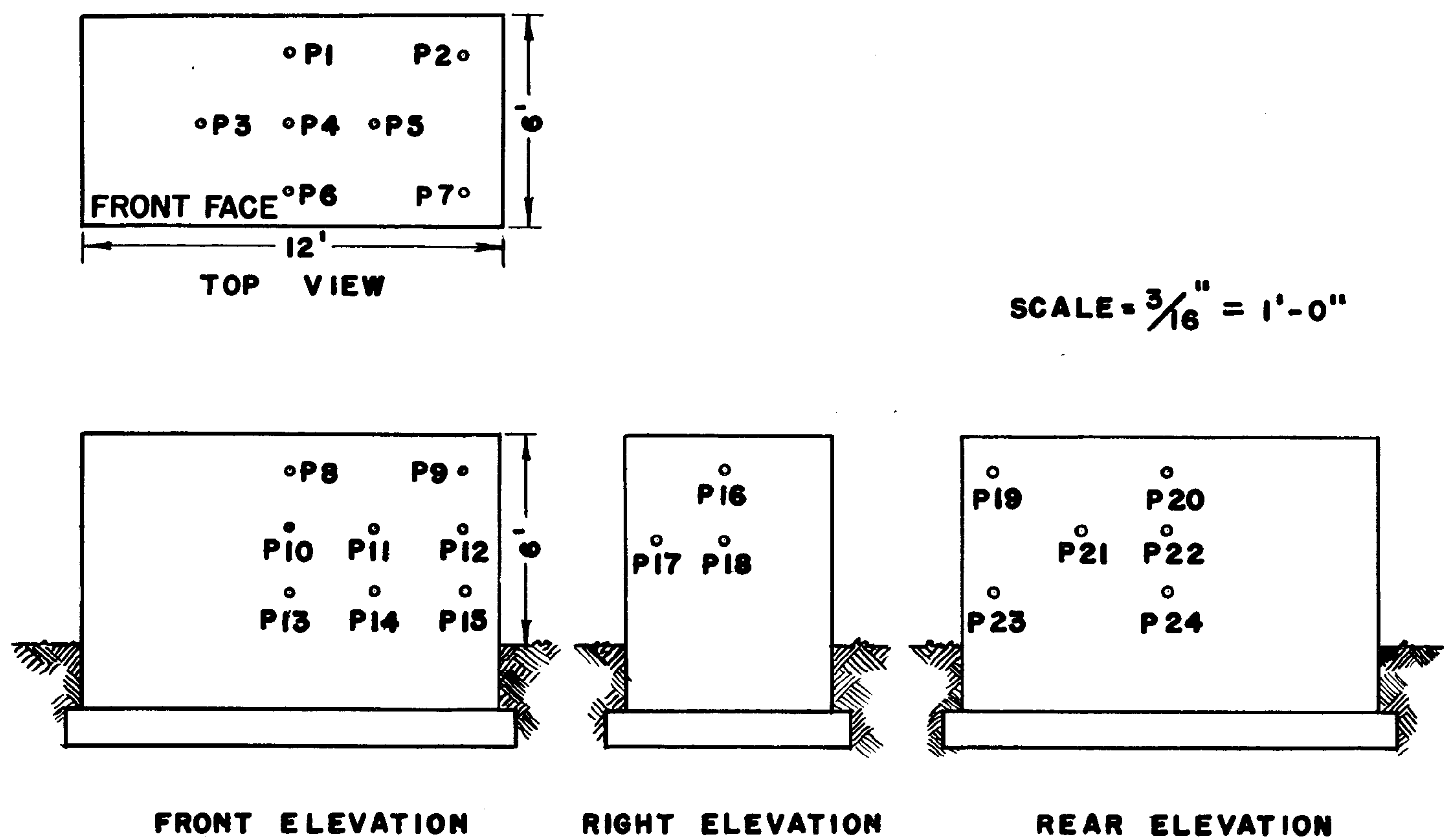

Fig. 2.6 Gage Layout for 3.1s and 3.1t Structures

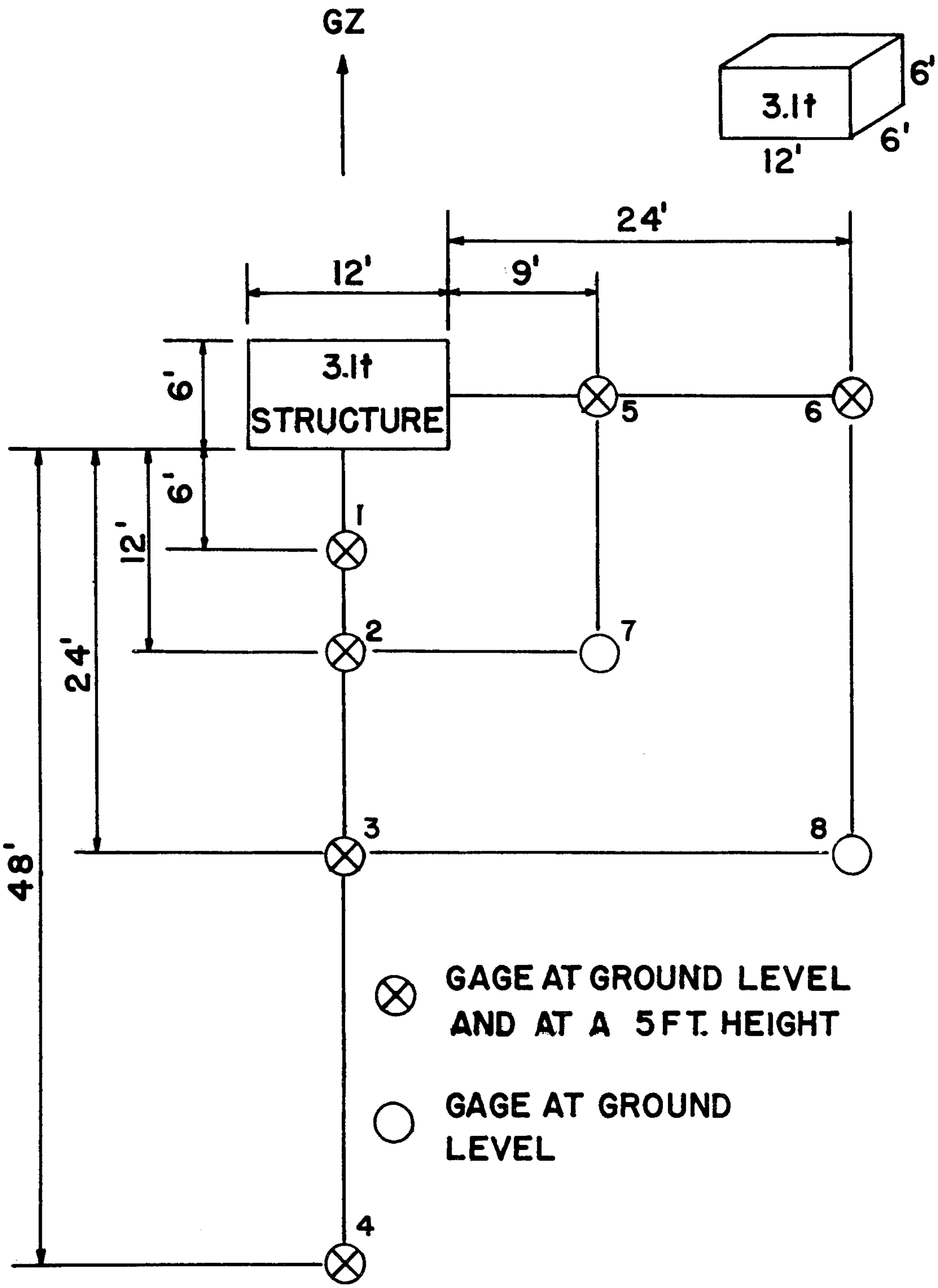

Fig. 2.7 Gage Layout for Diffraction Study

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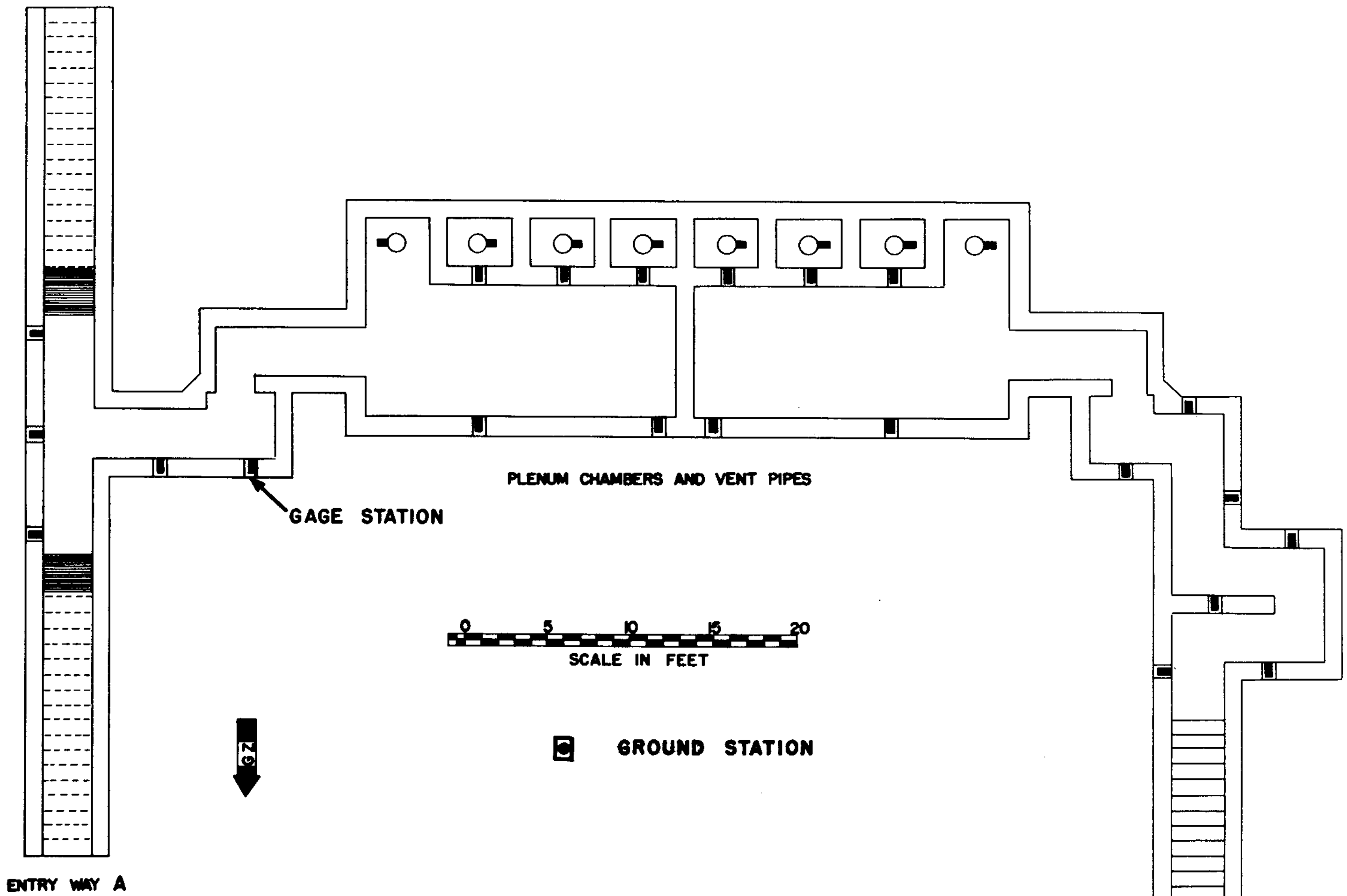

Fig. 2.8 3.7 Underground Structures

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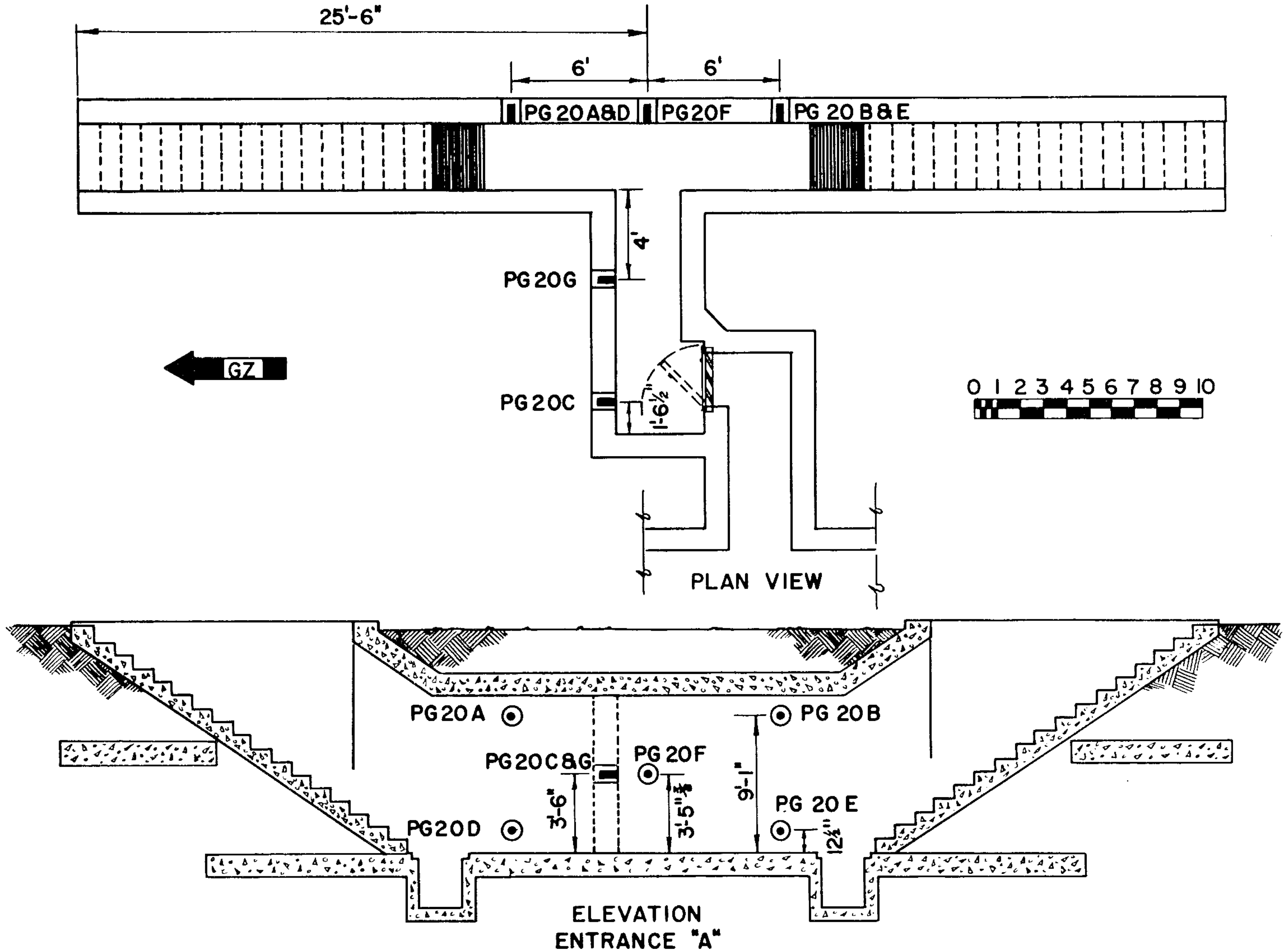

Fig. 2.9 Gage Layout for 3.7 Structure, Entryway A

[redacted]

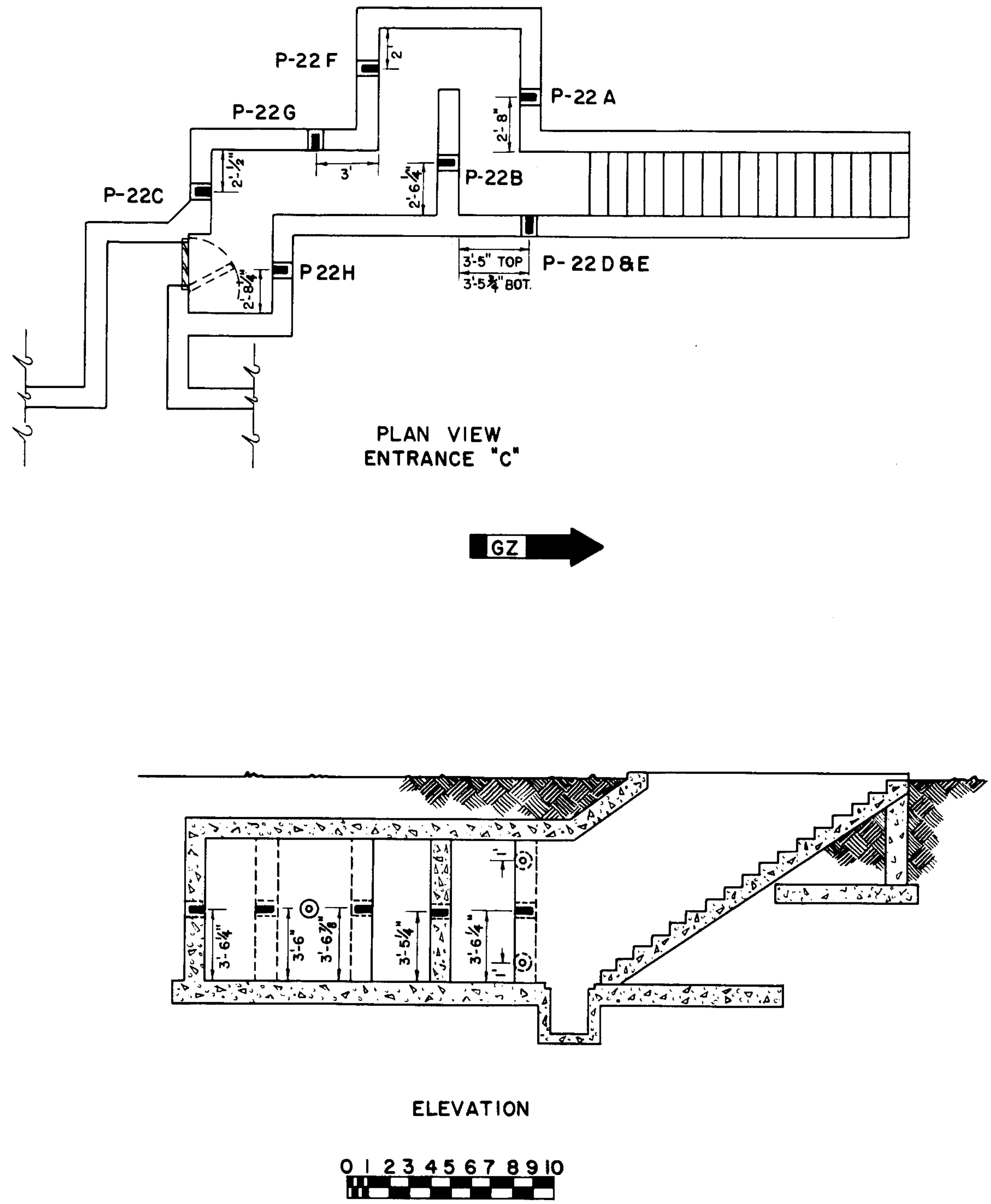

Fig. 2.10 Gage Layout for 3.7 Structure, Entry-way C

[redacted]

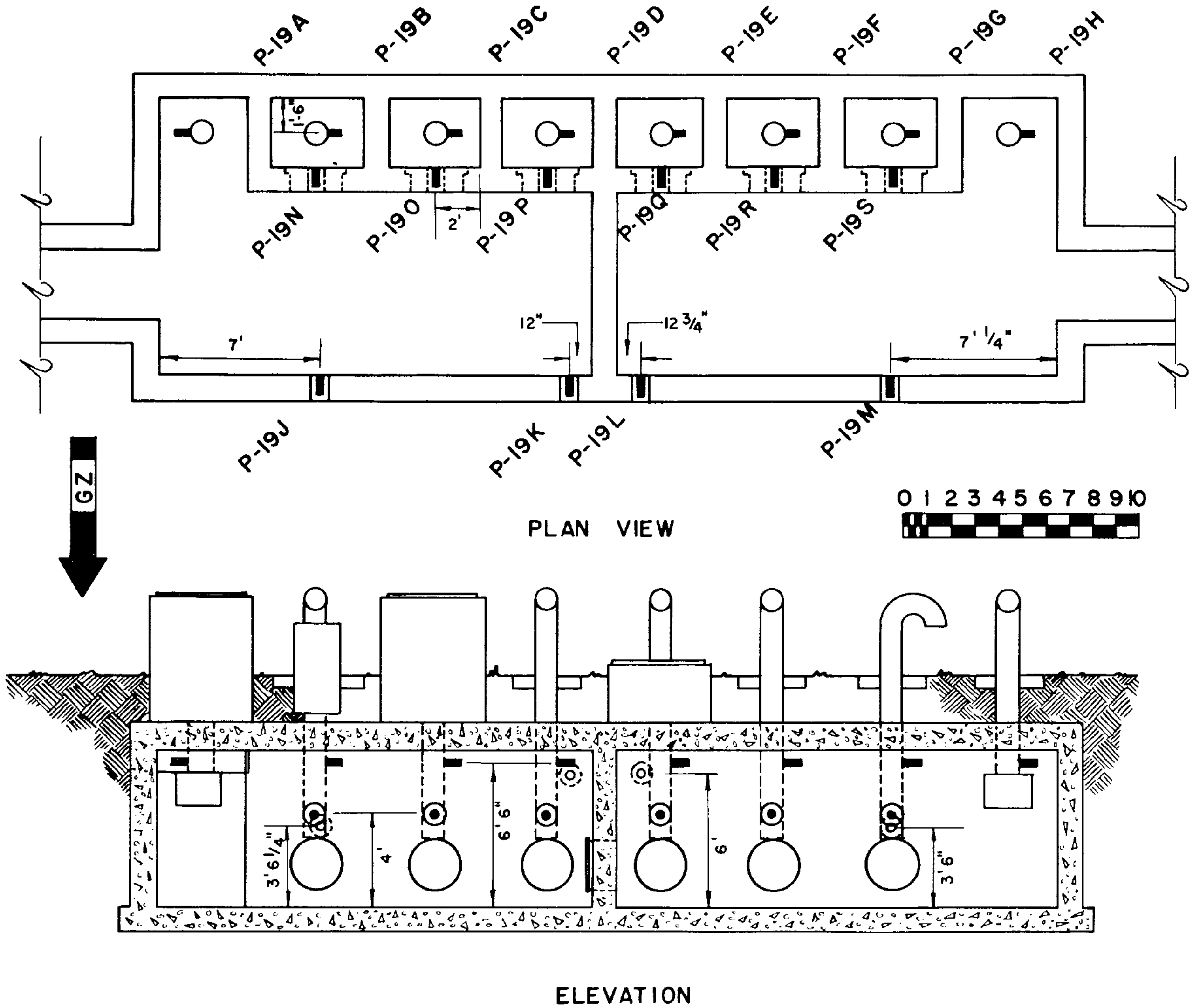

Fig. 2.11 Gage Layout for 3.7 Structure, Vents and Plenum Chambers

ways to check the symmetry of the shock wave at this location with respect to the main blast line. The gages in the eight instrumented vent pipes were connected to their respective oscillator-amplifiers by means of short lengths of RG-22/U cable. The 15 gages (8 channels) of entryways A and C were distributed over all the recorders of trailer 2; the remaining 19 gages (11 channels) of the 3.7 structure were recorded by trailer 1. Identical instrumentation was employed on Shots 9 and 10.

2.2.5 Project 3.9 Layout

Five foxholes were instrumented for Project 3.9, two at 4100 ft and three at 7000 ft (Fig. 2.12). Each foxhole (6 ft long, 2 ft wide and 4 ft deep) was lined with plywood to retain its shape. A gage in a cover-plate baffle was placed 6 in. from the bottom of each foxhole, except for Shot 10 where the gages in foxholes 1 and 2 were placed flush with the bottom of the foxholes. One position at 7000 ft was partially covered with a sheet of plywood. The foxhole signals were recorded in trailer 2.

2.2.6 Project 3.13 Layout

The uncovered gable shelter, 3.13b, was instrumented with 12 pressure gages as shown in Fig. 2.13. Because of the limited wall thickness, RG-22/U cable connected the gage mounts to the oscillator-amplifier housings fastened to the floor of the structure. A special gage mount was placed in the center of the structure with the gage 2 ft from the floor to measure pressure inside the building. The gage signals from 3.13b were recorded in trailer 1. This structure was instrumented only for Shot 9. The Ballistic Research Laboratories also made measurements on this structure.

2.2.7 Project 3.19 Layout

The tree stand at 6500 ft was instrumented with 15 gages for Shot 9, 12 at ground level and one each at heights of 10, 35, and 60 ft (Fig. 2.14). The three gages on the poles were mounted in circular baffle plates and connected to the oscillator-amplifier with RG-22/U cable. These baffles were oriented 5° off intended ground zero in such a way as to provide pressure incidence on the front face of the baffle (gage entry side) rather than on the back face in case of moderate bombing error. The records for this project were recorded in trailer 2. For Shot 10 the instrumentation was reduced to four gages, P4, P101, P102, P103 (Fig. 2.14). Other agencies also made measurements in the tree stand.

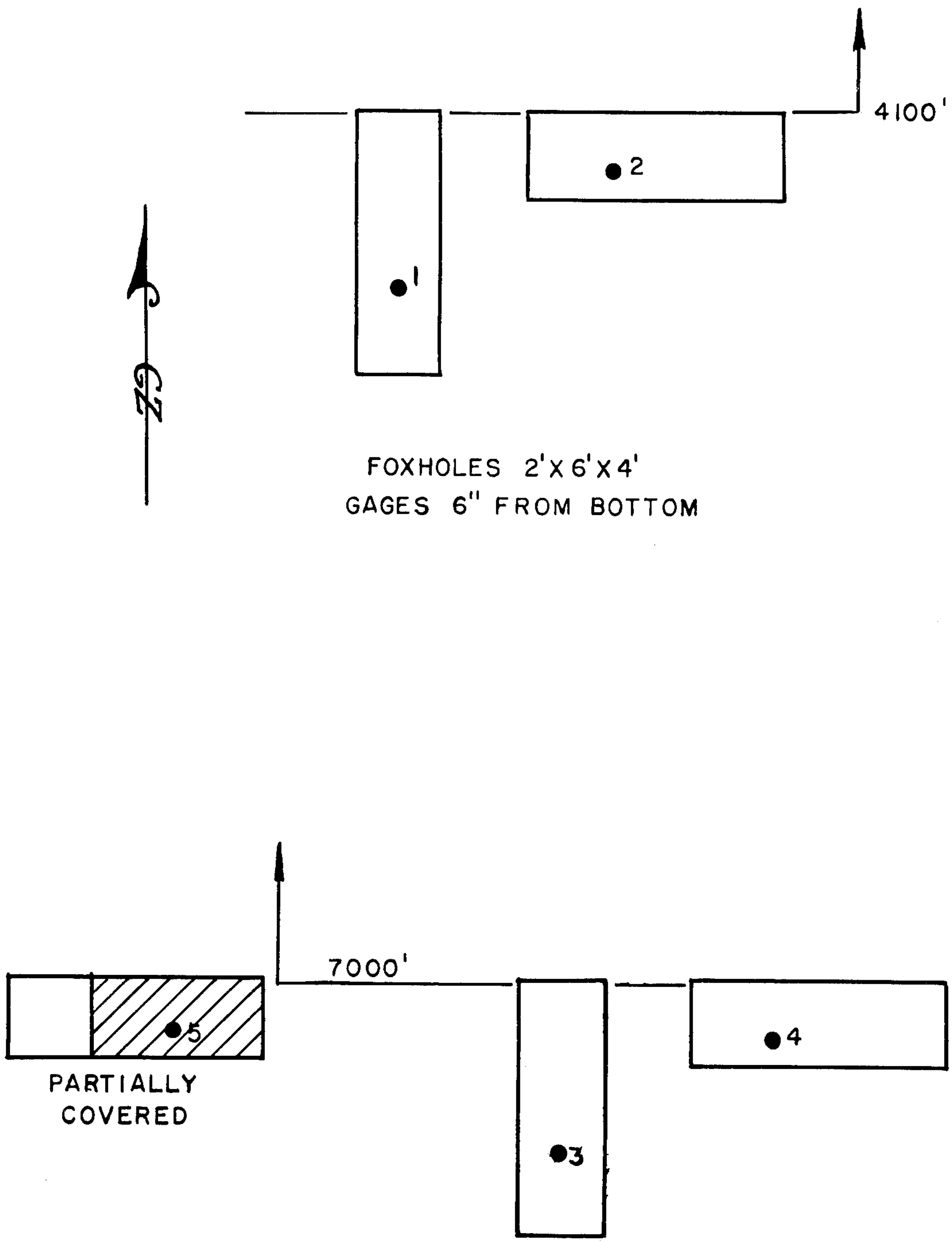

Fig. 2.12 Gage Layout for Project 3.9 Foxholes

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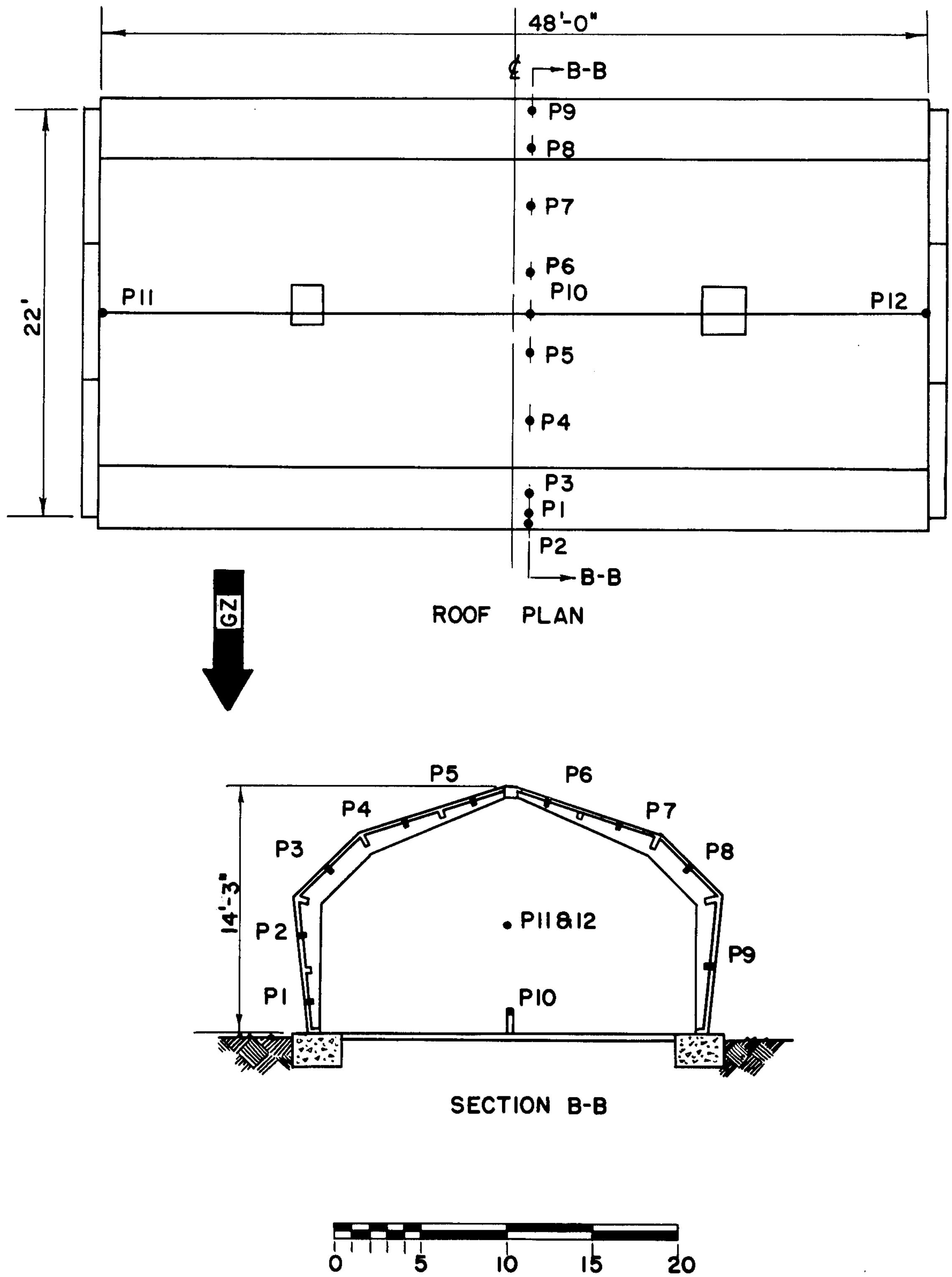

Fig. 2.13 Gage Layout for Project 3.13b Uncovered Gable Structure

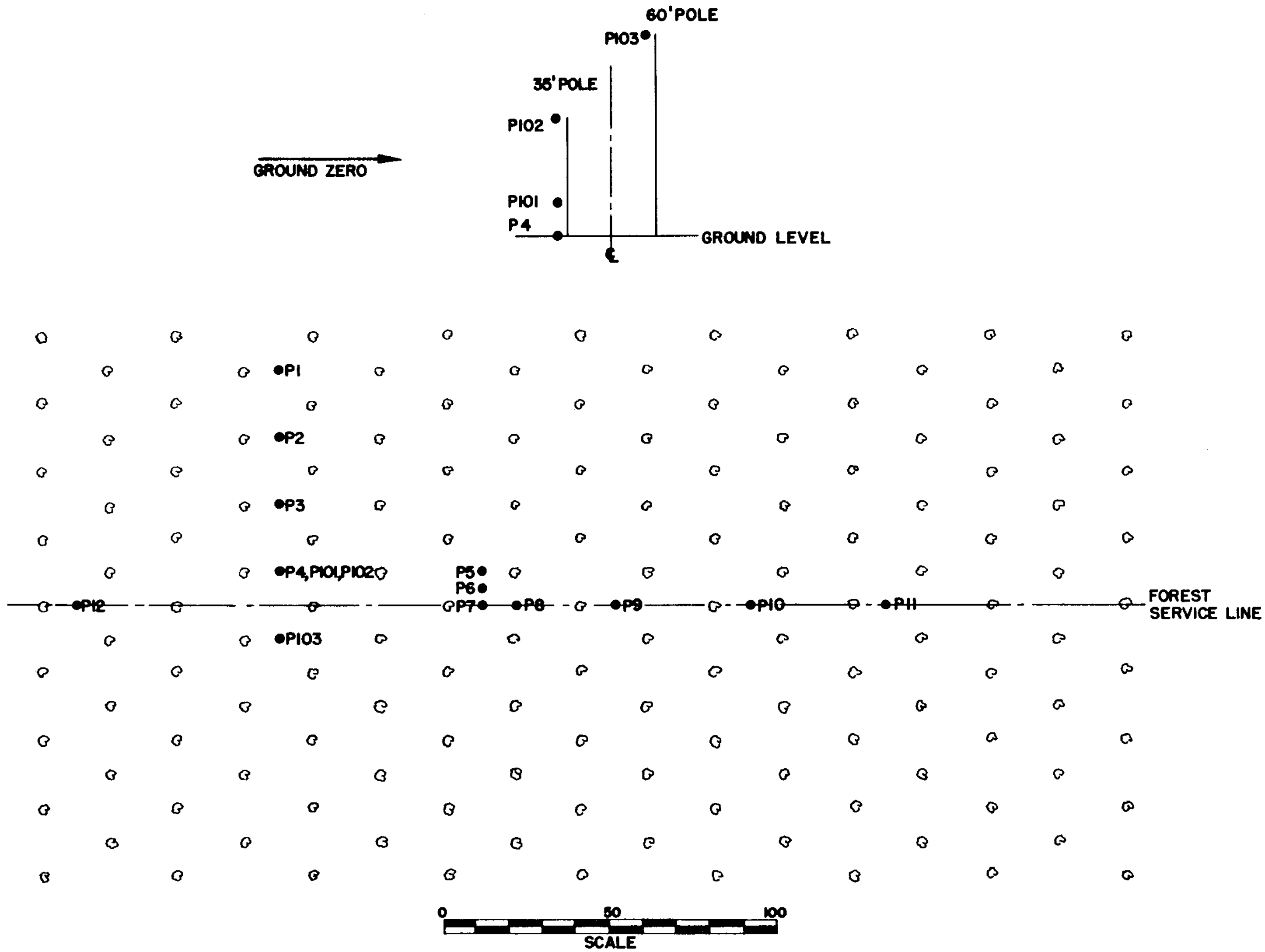

Fig. 2.14 Gage Layout for Project 3.19 Tree Stand

CHAPTER 3

RESULTS

3.1 GENERAL

Good quality, high signal-to-noise ratio records were obtained on this operation. The high quality of these records is attributed to the improved characteristics of the Wiancko gage (as compared to the previously used Bendix gage), the relatively wide frequency deviation employed on this operation, and the judicious predictions of pressure by the Program 3 agencies with the corresponding correct selection of available gage ranges. A total of 233 gages were used for Shots 9 and 10; all gages and channels functioned properly up to zero time. However, no pressure records were obtained from one station on Shot 9 and eight stations on Shot 10 because of gage failure just at zero time, and on Shot 10 forty-eight records were partially or completely lost shortly after zero time due to cable breakage. A summary of the instrumentation results are tabulated in Table 3.1.

TABLE 3.1 - Summary of Instrumentation Results

Project	Number of Gages		Number of Complete Records		Signals out at Zero Time		Partial Records		Thermal Shift	
	Shot 9	Shot 10	Shot 9	Shot 10	Shot 9	Shot 10	Shot 9	Shot 10	Shot 9	Shot 10
3.1s	24	24	24	0	0	0	0	24	7	0
3.1t	24	24	24	23	0	1	0	0	0	0
3.1u	14	14	14	11	0	3	0	0	0	0
3.7	34	34	33	5	1	5	0	24	1	0
3.9	5	5	5	5	0	0	0	0	0	0
3.13b	12	0	12	0	0	0	0	0	1	0
3.19	15	4	15	4	0	0	0	0	0	0
Total	128	105	127	48	1	9	0	48	9	0
Total, Shots 9 and 10	233		175		10		48		9	

No complete explanation has been found to explain the gage failures at zero time on both Shots 9 and 10 except to note that post-shot tests have shown the electrical Q of the gage coils to be substantially lower than their pre-shot values. It may be that the large ground currents produced at the time of detonation of the weapon placed an excessive load on the gages with marginal electrical properties, effectively lowering the Q's and thus stopping oscillator operation.

Cable breakage which caused the partial or complete loss of 48 records on Shot 10 occurred in a number of ways. In the 3.1s structure, all cables parted in tension when the structure was displaced approximately 25 ft. In the 3.7 underground structure, some cables broke in tension when parts of the structure or the cable conduits were displaced; other cables broke in shear, particularly where the cable entered the cable trench from the cable conduit. In most cases, the cable conduit was not flush with the bottom of the trench and therefore loose fill dirt was both above and below the cable. The air blast was of sufficient force to depress significantly the whole mass of fill, pushing the cable against the sharp edge of the relatively fixed conduit and thus shearing the cable.

On Shot 9 some records showed a considerable base line shift starting about 0.1 sec after zero time. Post-shot surveys showed the shift to be due to the effect of thermal radiation on the gage. The position of the affected gages was such as to allow direct thermal radiation to enter the pressure inlet of the gage and strike the twisted tube which is thermally sensitive. On those records where complete thermal recovery was not reached before the shock wave arrived, the trace produced a distorted representation of the pressure wave. However, the true nature of the pressure wave can be reconstructed without undue loss of fidelity by graphical means. For Shot 10 small aluminum shields were placed approximately 6 in. in front of those gages which would be subjected to direct thermal entry into the pressure tube. These shields were designed either to burn away or blow away without impeding or distorting the pressure signal at the gage. They proved quite effective in performing this shielding function.

The original records of each project have been delivered to the cognizant agency. Copies of all the records have been delivered to the Director, Program 3, and copies of the Project 3.1 records have been sent to the Ballistic Research Laboratories, Air Materiel Command, Stanford Research Institute, and Sandia Corporation.

The data analysis of the records obtained by the NOL for the Program 3 projects is being performed by the cognizant agencies listed in Sec 1.1, and the results will be reported in the reports of these agencies.

3.1.1 Project 3.1s Results

On Shot 9 twenty-four records were obtained. The records from the seven gages on the top surface, positions P-1 through P-7, showed

the thermally induced base line shift; graphic reconstruction of the wave form is necessary.

On Shot 10 aluminum thermal shields were used on all the gages mounted in the front face of the structure, and as a result no thermally induced base line shift occurred. Records were obtained from all twenty-four stations up through the early portions of the pressure history. However, all signals stopped at from 250 to 800 ms after the shock arrival due to the breaking of instrumentation cable incurred by the 25 ft displacement of the structure. There was a considerable amount of oscillation in the records and these oscillations have become associated with spurious acceleration effects as discussed in Chapter 2 and also perhaps with the nature of the precursor phenomenon.

3.1.2 Project 3.1t Results

All twenty-four records were obtained on Shot 9 and twenty-three records were obtained on Shot 10 (gage P-15 failed at zero time on Shot 10). No thermally induced base line shift occurred on Shot 9; however, for Shot 10 the geometry of the gage positions on the front face of the structure with respect to planned burst position was such as to dictate the use of the aluminum shields. Accordingly, shields were employed and no base line shift occurred. The records for Shot 10 showed the general precursor characteristic waveform of relatively smooth, slow variations of pressure; only the three stations on the side of the structure, P-16, 17, and 18 showed violent, large amplitude, high frequency oscillations superimposed on the trace.

3.1.3 Project 3.1u Results

All fourteen records were obtained on this project on Shot 9. Eleven records were obtained from the fourteen stations instrumented on Shot 10; at the 5 ft levels of stations 1, 2, and 3 the signals failed at zero time.

The records of the 5 ft high gages show much more oscillation in the trace than the ground mounted gages. This is ascribed chiefly to the whipping action of the pole and the resulting gage acceleration effect. For Shot 10 the 5 ft gage records are especially poor in this respect, and this may not be surprising considering the fact that many of the 5 ft poles were badly bent.

As stated in Sec 2.2.3, the baffles for the aboveground gages were oriented at an angle of 5° from the intended ground zero, and this orientation was followed by all the instrumenting agencies. This procedure was decided on in the light of a study on the effect of baffle plate orientation on dynamic pressures (5). The actual bombing errors introduced an additional 22° on Shot 9 and 3° on Shot 10, making a total orientation angle of 27° and 8°, respectively, of the baffle plate with respect to the direction of propagation of the shock front.

The large orientation angles obtained, particularly on Shot 9, may have introduced appreciable errors in the measurement of the "free field" pressures. This is discussed more fully in the 3.1u report (6).

3.1.4 Project 3.7 Results

Of the 34 gages instrumenting the 3.7 underground structure, thirty-three records were obtained on Shot 9. The gage oscillator unit at station PG-20G in entryway A ceased to operate at zero time. The measurement at the ground position, PG-19T, showed the thermally induced base line shift.

On Shot 10 only five complete records were obtained from this structure, namely, those from stations PG-19A, B, C, O, and T. The five signals from positions PG-19D, J, M, and N, and PG-20A failed at zero time. The remaining twenty-four signals failed at or shortly after the arrival of the shock wave due to cable breakage.

3.1.5 Project 3.9 Results

Each of the five stations in the foxholes gave excellent records on both Shots 9 and 10.

3.1.6 Project 3.13b Results

On Shot 9 twelve gage records were obtained on and in the 3.13b aboveground gable shelter. One gage, P-3, exhibited the thermal effect described previously. This one gage and no other, was in a position on the structure favorable for the entrance of thermal radiation into the twisted tube of the gage. Shot 10 was not instrumented.

3.1.7 Project 3.19 Results

All fifteen records in the tree stand were obtained on Shot 9 and all four of the stations instrumented on Shot 10 produced records.

As stated in Sec 2.2.7, the aboveground baffles were oriented at an angle of 5° from the intended ground zero. (See also Sec 3.1.3). The actual bombing errors introduced an additional 7° on Shot 9 and 1° on Shot 10, resulting in a total orientation angle of 12° and 6°, respectively, of the baffle plate with respect to the direction of propagation of the shock front. For these small angles the effect of the baffle orientation should be negligible.

APPENDIX A

USE OF INDENTER GAGES BY NOL IN PROGRAM 3

A.1 INTRODUCTION

This appendix describes briefly the application made of indenter gages by the NOL to measure peak pressure for several Program 3 projects. As mentioned in Sec 1.1.2, the primary purpose of the use of indenter gages was for the evaluation of indenter gages as a method for measuring peak pressures on structures and for other non-free-field measurements. The modified indenter used is described in reference (7) and detailed analysis of the results are presented in reference (1).

A.2 LAYOUT OF GAGES

Three indenter gages each were installed in structures 3.1s and 3.1t. The three gages were flush mounted on the front faces of these structures in a position to the left of center corresponding to the position of gage P-11 (Fig. 2.6) to the right of center.

Three indenter gages were installed in each of two 3.9 foxholes. The indenter gages were mounted in the same location as Wiancko gages P-2 and P-4 (Fig. 2.12).

A.3 RESULTS

The results are reported and discussed fully in reference (1). In qualitative summary, the indenter gages gave poor agreement with Wiancko gage pressures when mounted in the 3.1s and 3.1t structures, but gave good agreement with Wiancko gages when mounted in the 3.9 foxholes.

APPENDIX B

DIRECTIONS FOR READING NOL FM RECORDS

B.1 RECORD PRESENTATION

The correct interpretation of any record depends in large part upon the understanding of the instrumentation system used to obtain the record and an evaluation of the characteristics of the system as it pertains to the presentation of the final form of the record. The details of the NOL FM magnetic tape system are described in this and other reports (3) (4); this report provides some guidance for the interpretation of the records in terms of the known characteristics of the instrumentation system and it also gives the mechanics for reducing the records to numerical data.

A brief resume of the instrumentation follows: The Wiancko inductance type pressure gage (2) operated in a frequency modulation system. The inductance element of the gage was part of the frequency determining tank circuit of a Hartley oscillator. Pressure variations experienced by the gage produced inductance variations which changed the rest frequency of the oscillator in conformity with these pressure variations. The rate of change of the oscillator frequency was proportional to the rate of change of the forcing pressure function while the frequency excursion or deviation was proportional to the amplitude of the pressure function. The damped frequency characteristic of the pressure sensitive element of the gage limited the upper frequency response of the system to approximately 800-1000 cps. Design considerations limited the frequency deviations of the system to approximately a minus 8 per cent frequency shift for the nominal pressure amplitude rating of the gage. On UPSHOT-KNOTHOLE two gages were multi-plexed. One gage provided the frequency modulating intelligence for an oscillator operating at a rest frequency of 15.4 kc, and the other gage frequency-modulated another oscillator centered at 10.7 kc. Interference between the two signals was negligibly small.

The mixed frequency-modulated signals were recorded on magnetic tape at the time of the tests and played back at a later date. The tape recording and reproducing machines and the tape material itself introduced an undesirable frequency modulation component and this extraneous signal manifested itself as "flutter" or noise on the final

record. This flutter was of a random nature, inherent in the machines and tape and was held to approximately 0.15 per cent of the frequencies recorded. It resulted in a signal-to-noise ratio of approximately 50 to 1 for full scale pressure signals.

In playback the multi-plexed signals were separated by means of band-pass filters and the frequency modulations of the center frequencies were changed into amplitude variations by discriminator units. Negligible distortion of signals was introduced by the discriminators. The outputs of the discriminators were applied to strings of a recording galvanometer to provide the final photographic records.

The over-all recording and reproducing system was calibrated frequency-wise for each record, (and in record reduction the frequencies were converted into pressure values). The following frequency steps were put on each record for each of the two channels: 15.7, 15.4, 14.8, and 14.2 kc, and 10.9, 10.7, 10.3, and 9.9 kc. (The top trace on all oscillogram records was the 15.4 kc channel.) The frequency system and the recording galvanometers were linear so that no distortion of the records resulted from these elements of the system.

Tuning fork controlled timing lines were put on each record at 10 ms intervals with the 100 ms lines accented to facilitate counting. Unfortunately, the drive mechanism of the recording galvanometer oscillograph ran erratically at times giving non-linear paper speeds and an apparent changing time scale. However, the timing markers are accurate to within $\pm$ 0.05 per cent and interpolation between timing marks should be valid for most requirements. The recording galvanometer was run at two speeds to give low speed records with a compressed time scale and high speed records with an expanded time scale. The low speed records are useful in determining gross characteristics of the pressure history, time of arrival of the shock wave, positive and negative phase durations, and impulse data. The high speed records (usually only of the initial portion of the pressure-time history) are used for peak positive pressure measurements and a detailed study of the regions of interest. A photographic reproduction of an actual pressure-time history in low and high speeds is shown in Fig. B.1.

B.2 GAGE CALIBRATION

All gages were statically and dynamically calibrated. Static calibration consisted of applying pressure in steps of known value to the gage operating in an oscillator and noting the frequencies obtained. This information was then plotted and thus a pressure versus frequency calibration curve for each gage was obtained. In the calibration procedure, the gage was pressure cycled through positive values (up to and greater than 1.5 times the nominal pressure rating of the gage) and negative values (by means of a vacuum pump). The calibration curves were drawn through only those data points obtained on the increasing positive and increasing negative excursions of pressure. (The curve should be used only between the extreme plotted data

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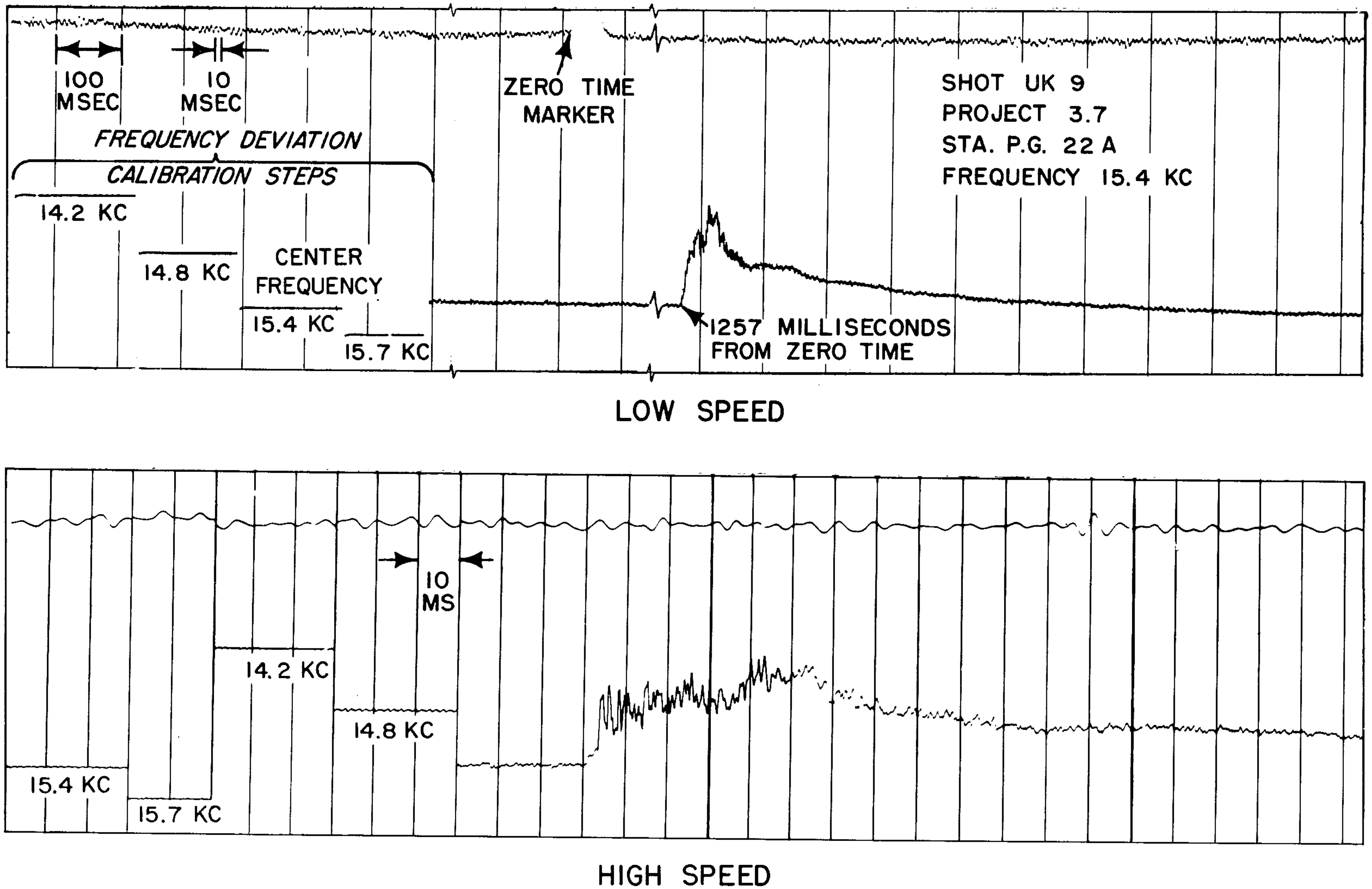

Fig. B.1 - Pressure-Time Record

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points and not beyond.)

It is to be noted from the calibration curves and the tabulated data on the graphs, that the gages are non-linear (approximately 5 per cent of nominal range) and show a small degree of hysteresis. The non-linearity of the gages precludes the use of a convenient linear pressure scale for the oscillographic records, and it also makes necessary the addition of a correction factor for planimetered impulse measurements made on these original pressure-time records. The scale values are obtained directly from the calibration curves and are accurate to $\pm$ 2 per cent. It is to be noted that only those pressure values in the initial increasing positive phase and the increasing portion of the negative phase are correct as obtained from either the calibration curves or the scales. Pressure values from other portions of the record are in error by the amount of hysteresis present at that portion of the curve; for most applications, this error would be negligible.

The dynamic calibration of each gage was made with a pressure chamber which imposed a rapidly rising (0.2 ms) positive pressure step on the gage. Three calibrations were made on each gage, one at 0.5 nominal range, the second at nominal range, and the third at 1.5 nominal range. Non-linear damping was evident for the majority of gages and also, some gages exhibited "creep" - the slow rise (of the order of 5 to 25 ms) to maximum pressure after an initial fast rise to about 0.9 of maximum value. Reproductions of the dynamic calibration characteristics similar to Fig. 2.2, are stapled to each static calibration curve and provide valuable information as to the behavior of the gages under transient pressure loadings. Timing markers on these records are at 0.5 ms intervals.

B.3 RECORD READING

B.3.1 Peak Positive Pressures

The high speed records are used to determine positive pressure values. The first task is to determine the point or points to be read, i.e., to determine the significant pressure signals on the record. Three factors are important in determining whether any particular part of the trace is real, i.e., pressure induced only. First, the noise or flutter level of the record should be observed just prior to shock arrival. This gives the order of magnitude of the possible flutter-induced deviation of any point of the record from the true pressure signal. For most records it was possible to keep the flutter level low in comparison to the signal by operating the gages near their nominal range. A second factor to be observed is the photograph of the dynamic characteristic of the gage. The degree of overshoot and creep, if any, as well as the frequency response and duration of ringing of the gage when shock excited, is indicated by these photographs. If the forcing pressure function is a "true" shock or has a

rise time equal to or less than the gage response time (0.3 to 0.8 ms), some overshoot and ringing is to be expected on the record. On the other hand, however, if the pressure rise time is longer than the response time of the gage, very little or no overshoot or ringing will be realized. The third factor to be observed is the sensitivity of the gage to extraneous phenomena such as acceleration and heat.

Prompted by the UPSHOT-KNOTHOLE results which showed many records, particularly on Shot 10, with high and low frequency oscillations superimposed on the main pressure wave, further study of the Wiancko pressure gage was undertaken, particularly as regards its sensitivity to acceleration (2). The investigation shows that the Wiancko gage used by NOL is acceleration sensitive to a substantial degree. (A 20 psi gage will give the equivalent of 1 psi signal when excited by a 10 g drop.) Further, they are sensitive in at lease two main modes - a designed torsional mode and an extraneous cantilever mode. The high frequency acceleration effect, 700-1200 cps, has the same period as the damped gage ring frequency (as indicated by the dynamic calibration photograph) or one of the three cantilever modes. The lower frequency, 300-500 cps, is due to one of the cantilever modes of the long sensing element of the gage and has been excited by means of a shake table in the laboratory.

Trying to correlate the laboratory determined pressure and acceleration characteristics of the gage with the actual records obtained in the field is made difficult by the seemingly unorthodox behavior of either the gage or the incident pressure forcing function, or both; some records showing high pressures with fast rise times have very little high frequency oscillations, and other records with lower pressures and 20-30 ms duration increases of pressure, show violent oscillations. A survey of all the records both on Program 1 and Program 3 show that the violent high frequency oscillations occur almost exclusively in the region of the well developed precursor wave and 20-30 ms after the arrival of the first pressure signal.

Since the oscillations under discussion do not seem to decay exponentially with time, it is reasonable to assume that energy was being fed to the gage sustaining these oscillations. There are two ways at least in which this could take place: the gage baffle plates, vertical and flush mounted, can be excited by either pressure pulses or drag forces or high velocity missiles and then impart their energy to the gage via acceleration (2)(8); or the gage itself could be excited by a rapidly varying pressure signal. Shock excitation of the baffle plate does not appear to affect the gage unduly. However, it is possible that sustained oscillation of the baffle plates could excite the gage for the duration of the sustaining force. The mechanism for sustaining this oscillation in the baffle plates is hidden for the present in the unknown true behavior of the precursor. It may be that sufficient energy is imparted to the dust to sustain oscillations in the baffle mounting plates. (To test this hypothesis the mounting plate and gage were sand blasted with an available industrial sand blasting rig; however, no spurious signals were produced.)

Of course, the possibility remains that the precursor wave itself had a rapidly varying somewhat cyclical pressure history with the gage trying to follow these variations. In addition to the 700-1200 cps frequency variations, the 300-500 cps frequency variations of considerable time duration also are believed to be acceleration effects rather than pressure variations.

In summation it may be definitely stated that whatever the real reason for this high frequency large amplitude oscillation, whether it be acceleration effects or pressure induced, it is apparent that since this oscillation occurs at the gage torsional or cantilever frequency, its amplitude certainly and its frequency probably are not true representations of the actual pressures at the sampling point.

Therefore, for record reading purposes, it is suggested that a line be faired through these extraneous signals for effective pressure values. This may not be the true pressure value, it is admitted, but impulse-wise, it may be considered the effective pressure.

A word of caution is necessary. Many of the spikes and oscillations on the records are true pressure signals and should not be discounted. As a general rule, it is safe to assume that if the period of the pulses on the record is the same as the shock induced gage ring, the recorded amplitude is incorrect. A train of such impulses should be faired through for a more correct pressure value.

When the point (or points) to be read on the record has been selected, the positive pressure values are established in the following way (See Fig. B.1).

a. Measure the amplitude of the known frequency calibration step in some convenient unit such as 1/50 of an inch.

b. Measure the displacement of the point to be read from the preshock arrival base line in the same unit.

c. The frequency of this pressure excursion is given by

$$\frac{\text{pressure signal amplitude}}{\text{calibration signal amplitude}} \times \text{calibration frequency.}$$

d. Subtract this pressure signal frequency from 15.4 kc (or 10.7 kc depending upon the center frequency at which the gage was used).

e. Convert this new frequency value into pressure by means of the gage calibration curve.

The measured pressures will be accurate to within $\pm$ 2.5 per cent.

No correction is necessary for the possible slight displacement of the pressure trace base line from the 15.4 kc (or 10.7 kc) calibration step. However, where the base line shifts due to the thermal excitation of the gage, a correction is necessary. The thermal shift can be recognized by the rather rapid shift of the trace up or down starting approximately 0.1 sec after zero time and its gradual return toward the pre-zero level. It is corrected for in the following manner:

a. Repeat steps (a) through (c) as above for the pressure signal frequency.

[redacted]

b. In a similar manner, on the slow speed record, determine the thermally induced frequency shift measuring the displacement of the trace from the pre-zero base to the point of shock arrival.

c. (1) Subtract this value from 15.4 kc (or 10.7 kc) if this point is above the pre-zero base line. (2) Add this value to 15.4 kc (or 10.7 kc) if this point is below the pre-zero base line.

d. From the gage calibration curve, determine the corresponding pressure.

e. From the frequency obtained in step (c) above, subtract the pressure induced frequency shift obtained in step (a) above.

f. Determine the corresponding pressure.

g. Algebraically subtract the value obtained in step (d) from the value obtained in step (f). This is the true pressure value.

Where the thermally induced base line shift occurred, the records were corrected for this shift and replotted on the original record oscillogram to better depict the true wave shape. In making this correction and replot, it was assumed that the rate of return of the trace during the passage of the shock wave was the same as just prior to the arrival of the shock wave.

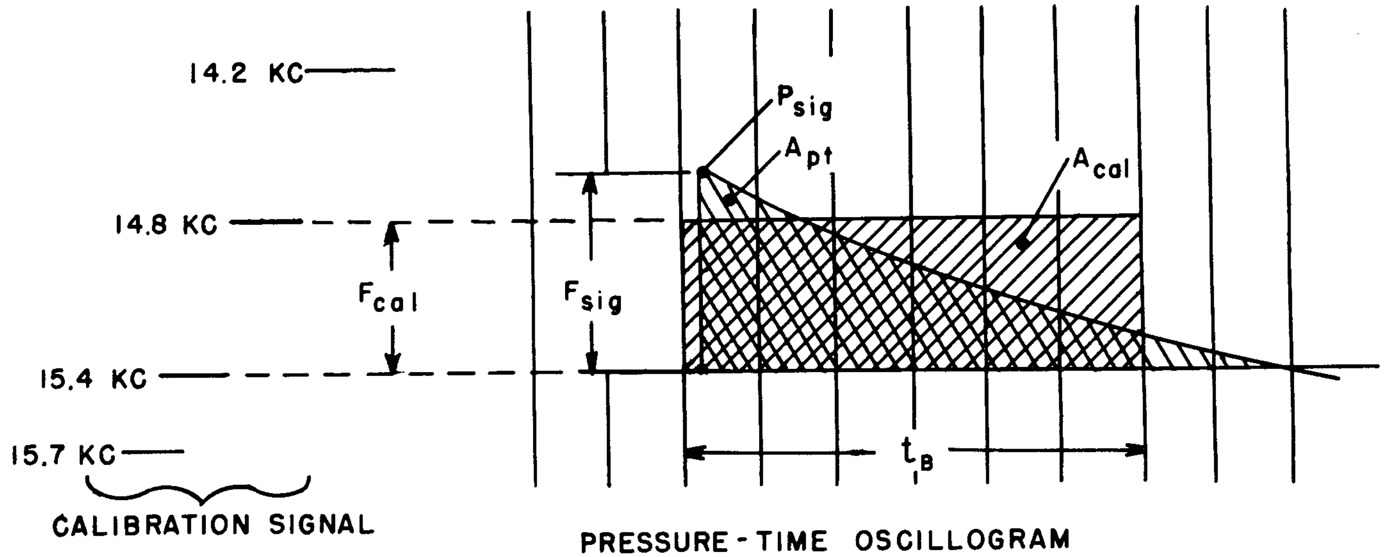
B.3.2 Negative Pressures

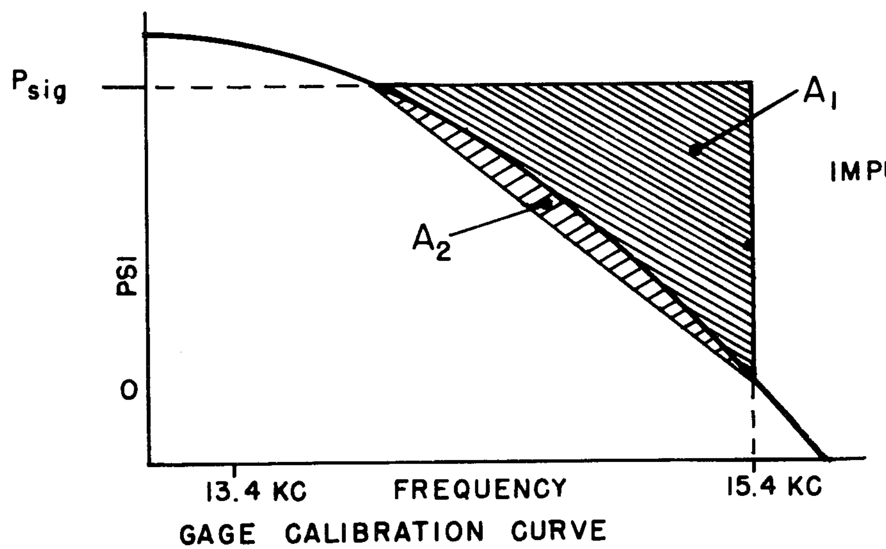
The slow speed records are used for determining negative pressures because of the gradual slope of the trace. The procedure outlined for the positive pressure values should be used for determining negative pressures.

B.3.3 Arrival Times and Positive and Negative Phase Durations

Ten millisecond timing lines transversely cross the pressure record, with the 100 ms lines accented. Zero time is indicated on the slow speed records of Shot 9 by a sudden step in a third trace of the oscillogram. On Shot 10 a nominal minus 2.5 sec signal (-2.454 secs actual) is shown on this third step instead of the zero time signal. On many records, zero time is evidenced also by a sharp spike on the pressure-time trace itself. All time measurements should be corrected to take into account the measured rather than the nominal values of the time-determining elements of the system. Therefore, multiply all measured times by 0.996 to obtain the true time between measured points to within 0.05 per cent accuracy.

Due to gage hysteresis, the durations of the positive and negative phases of the recorded trace are in error. The measured positive durations should be decreased by approximately 10 per cent and the measured negative durations should be increased by approximately 5 per cent. The error in duration measured then becomes approximately ± 8 per cent. This error, however, is only of second order effect in making impulse measurements.





$$\text{IMPULSE} = \frac{t_B \times P_{sig} \times F_{cal} \times A_{pt}}{A_{cal} \times F_{sig}} \left(1 + \frac{A2}{A_1}\right)$$

Fig. B.2 Impulse Measurement Diagram

B.3.4 Impulse

Impulse measurements can be made in a number of ways. Impulse measurements made directly on the oscillogram should be corrected for the slight distortion of the pressure trace caused by the non-linearity of the gage. The method employed at NOL (to avoid the tedious task of replotting the p-t curve on a linear scale) is an approximation method. The assumption is made that the pressure-time oscillogram is triangular, and determining exact corrections for this assumed p-t curve. These corrections are then applied to the area measurements of the actual p-t oscillogram. Only second order errors are introduced by this method, and the final impulse accuracy is approximately 5 per cent.

Positive impulse is found in the following way:

a. Measure the area A_{pt}, (Fig. B.2) of the positive phase of the p-t oscillogram in some convenient unit (with a planimeter).

b. Measure the area A_{cal}, of a convenient rectangle on the p-t oscillogram bounded by a known frequency calibration step, F_{cal}, and a measured time base t_B.

c. From previously obtained data, note the significant peak positive pressure, P_{sig}, and the corresponding frequency excursion F_{sig}.

d. Then $\text{Impulse}_{(\text{uncorrected})} = I_u = \dfrac{t_B \times P_{sig} \times F_{cal} \times A_{pt}}{A_{cal} \times F_{sig}}$.

e. On the gage calibration curve measure the areas A_1 and A_2.

f. Then, $\text{Impulse}_{(\text{corrected})} = I_u \left(1 + \dfrac{A_2}{A_1}\right)$.

[redacted]

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